PHASE DETECTOR (COMPARATOR) FOR THE AØ LASER

D. Y. Duose
Department of Electrical and Electronic Engineering, CSU Sacramento
Supervisor : James Santucci
Fermi National Accelerator Laboratory

Abstract - **The main objective of this (project) paper is to describe the design, building and testing of an external phase detector (comparator) for a laser system. This external phase detector will be used to confirm or refute the error signal obtained by the commercial phase locked box currently in use.**
Author Keywords: Phase Detector, mixer, Laser.

I. INTRODUCTION

Fermi National Accelerator Laboratory (FNAL) furthers the understanding of the fundamental nature of matter and energy by conducting basic research in high-energy physics and related disciplines. Fermilab does not conduct research independently but in collaboration with other facilities. One such collaboration is the photo-injector project known as AØ Photo-injector (AØPI): a group effort between FNAL, UCLA, INFN Milan, University of Rochester and DESY to prototype the low energy stages of a proposed electron-positron linear collider known as the TeV Electron Super-conducting Linear Accelerator (TESLA).

The laser driven Radio Frequency (RF) photo-injector is a source for, very short, high quality electron bunches needed for use in Free Electron Lasers (FEL), high-energy linear colliders, and in Advanced Accelerator Research and Development. A basic requirement for any laser system used to drive an RF photo-injector is to synchronize the laser pulses to the drive RF of the photo-injector cavity. It is essential to have every laser pulse in phase with the RF because once the relative phase is set; every laser pulse will arrive at the photo-cathode at the correct launch phase for acceleration. A commercial phase locked box (LightWave Electronics, Series 1000 Time Stabilizer) is utilized to keep the laser phase locked to the RF signal. The rigid requirement of TESLA is a phase jitter less than one degree of the RF corresponding to 2.1 pico seconds. The phase locked box uses a feedback loop to suppress the timing (phase) jitter via the following process: The reference signal (81.25 MHz) is divided by 2 and applied as the drive signal to an acousto-optic mode-locker. The actual phase of the 81.25 MHz on the laser output is picked up from a fast photodiode; a phase detector then compares the actual 81.25 MHz with the reference. The phase error signal from the output of the phase detector is applied to a phase shifter, which modifies the drive signal. The process repeats incessantly.

The main objective of this (project) paper is to describe the design, building, and testing of an external phase detector (comparator) for a laser system. This external phase detector will be used to confirm or refute the error signal obtained by the commercial phase locked box currently in use.

II. BACKGROUND

A. Photo-injector

The Photo-injector consists of an RF gun with high quantum efficiency photo cathode, an advanced laser system to produce photoelectrons from the cathode, and a super-conducting accelerator cavity. Fig1 shows a diagram of the AØ cave and photo-injector.

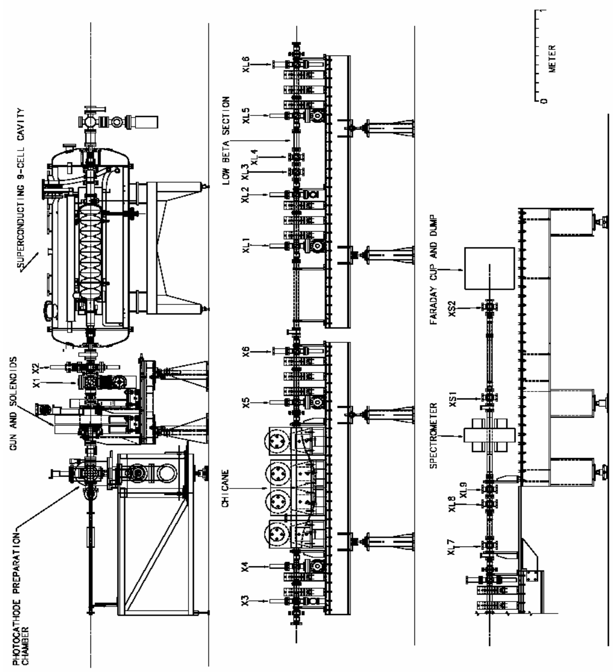

Fig 1: The Beamline of the A0 Photoinjector

The RF gun consists of a 1.5 cell, iris coupled pi-mode structure. A removable cathode plug coated with a high efficiency photo cathode material is fitted into the back of the gun. A klystron powered by a pulse transformer generates the RF power. The gun requires 3.0 MW of 1.3 GHz RF power to accelerate 4 MeV electrons for 0.8ms. A niobium-superconducting (SC) cavity makes up the rest of the accelerating section, which requires 200KW of 1.3 GHz RF power to accelerate 12 MeV electrons for 1.3ms.

The gun has 1.5 cells and is about 16.5 cm in length (35 MeV/m). The SC cavity has nine cells and just over one meter of active accelerating length (12 MeV/m). The RF frequency of 1.3 GHz has a cycle period of 760ps. The low level RF (LLRF) sources pertinent for accelerating cavities, the laser, and all other RF needs of the system are derived from a single master oscillator. Table 1 shows a list of frequencies, their use and relation to master oscillator [1].

9.027775 MHz	f_0	master oscillator
1299.9996 MHz	$144f_0$	RF (1.3 GHz) for gun and 9-cell
81.249975 MHz	$9f_0$	laser oscillator frequency
1.003086 MHz	$f_0/9$	pulse train frequency
0.250772 MHz	$f_0/36$	mixing, synch 1 Hz triggers
1300.250 MHz	$144f_0 + f_0/36$	mixing with transmitted RF

Table 1: Low-level radio frequencies in use and the relation to the master oscillator

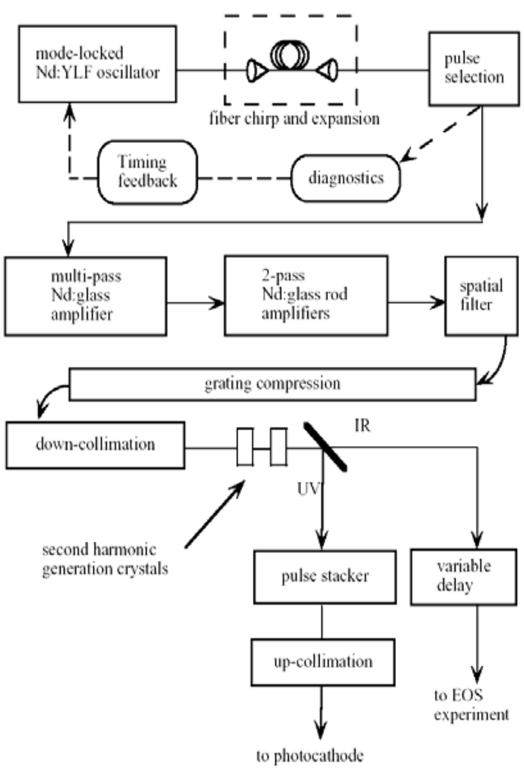

Fig 2: Block Diagram of the Laser System

The block diagram in Fig 2 shows the laser system in its entirety. It consists of an active mode locked Nd:YLF oscillator that generates the laser pulse train. The pulses then go through a 2.2km single mode fiber, which expands the pulse thereby, increasing the spectral bandwidth by a factor of 3. Subsequently, the pulse selection is done using Pockel cells (a fast switching element that discriminates between adjacent pulses 12.3 ns apart).

The selected laser pulses are then amplified to 6 x 10^5 gain saturation by a multi-pass Nd:glass amplifier.

Light from the multi-pass is sent to a two pass Nd:glass amplifier with two amplifier stages for a gain of up to 9.6 x 10^5. A pair of parallel plate gratings compresses (chirps) the bandwidth of the laser pulse. This chirped pulse is put through 2 non-linear crystals that quadruple the frequency from Infra Red (IR) to Ultra Violet (UV). The UV laser is then transported to the cathode in the photoelectron gun. Both the IR and UV laser beams are used in conducting different experiments.

B. Active mode-locked Oscillator

The active mode-locked oscillator at the beginning of the laser system is custom built and consists of commercial components mounted on an Invar plate. The components include a Quantronix 116 pump chamber that houses a 4mm diameter 79mm Nd:YLF rod (1% doping). A Krypton arclamp continuously pumps the rod with 27amperes passing through the lamp. A gold reflector surrounds the lamp and rod, and the entire pump chamber is cooled with de-ionized water. A pair of Brewster-angle thin film polarizers in the oscillator cavity ensures linear polarization. A circular iris in the oscillator cavity is used to constrict the transverse mode of the oscillator to be TEM_{00}, which is Gaussian in shape and has the lowest diffraction losses. The oscillator cavity is a linear resonator that has a defined length, thus resulting in free oscillation of laser modes occurring for modes with a gain greater than the cavity losses. Since each mode oscillates with a random phase compared to the others, the laser output will have large intensity fluctuations. To ensure minimum intensity fluctuations, all modes must have a stable phase relationship with each other [2]. This process, known as mode locking, is achieved via the use of a commercial acousto-optic modulator (Intra Acton Corp, model Ml-40623B1-3). Active mode locking makes it possible for the laser output to be synchronized with a reference signal. The laser is phase locked to the RF signal by means of the phase lock box with a phase jitter of less than one degree of the RF (requirement of TESLA) [1]. The laser relies on two frequencies from the LLRF: an 81.25 MHz sinusoidal signal for the mode-locked oscillator and a 1.003 MHz TTL pulse signal for laser pulse train selection. The phase locked box uses a feedback loop to suppress the timing (phase) jitter of the oscillator. The 81.25 MHz reference signal is halved and applied as the drive signal to the acousto-optic mode-locker. The actual phase of the 81.25 MHz on the laser output is picked up from a fast photodiode. The photodiode signal is detected as pulses 12.3 ns apart (81.25 MHz) as seen in Fig 3. The actual 81.25 MHz signal from the photodiode and the reference are compared using a phase detector. The phase error signal from the phase detector is applied to a phase shifter, which modifies the drive signal [1]. The block diagram in Fig 4 shows the operation of the phase locked box.

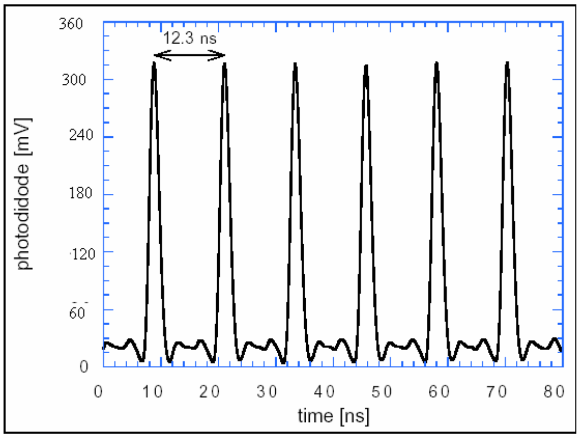

Fig 3: 81.25 MHz pulse train from the mode-locked oscillator

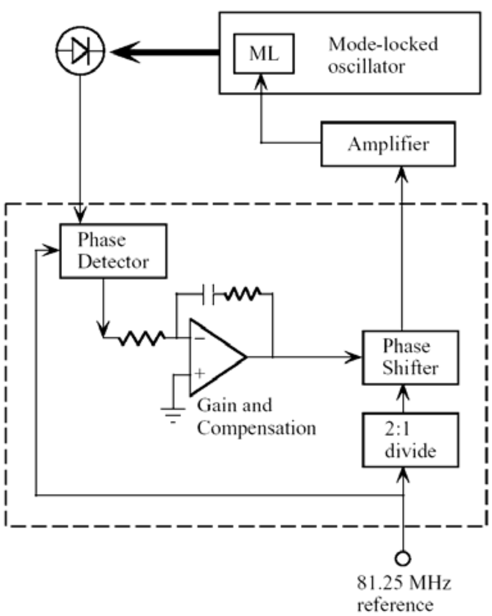

Fig 4: Phase locked box (in dashed box) compares the phase of the laser oscillator pulses to the reference and shifts the drive accordingly.

III. BASIC PRINCIPLES OF PHASE DETECTOR

A phase detector is a device that compares two input frequencies and generates an output that is a measure of their phase difference [3]. There are three types of phase detectors: Analog or multiplier (mixer), Exclusive-OR (The digital equivalent of the analog multiplier) and Digital phase-frequency detector. The main advantage of the analog phase detector over the digital ones is that it is capable of recovering a signal from low signal-to-noise input [4]. Because of the high noise associated with the photodiode signal, an analog mixer is the best choice for this particular phase detector application.

A double balanced frequency mixer can be used as a phase detector given that the two signals being compared have identical frequencies and unvarying amplitude. The actual 81.25 MHz signal from the photodiode and the reference signal fed into the phase detector meet this criteria. A double balanced mixer has 2 input ports, the Local Oscillator (LO) and the Radio Frequency (RF) ports. The output of the mixer is the IF port. For phase detector applications the output is a DC signal which is proportional to the phase difference between the two signals [5].

A. *Criteria for selecting Mixer for Phase detector Application*

A mixer being used as a phase detector operates in the saturation mode. The following must be considered when selecting a mixer for use as a phase detector [5]:

- A double balanced mixer should be used because it provides the desired isolation among ports. Isolation is a measure of the circuit balance within the mixer. It is defined as the ratio (in dB) of the power level applied at one port of the mixer to the resulting power level at the same frequency appearing at another port. When the isolation is high, the amount of "*leakage*" between the mixer ports is very small.
- The mixer must have a low dc offset so as to assure accuracy of detector in determining phase difference.
- Maximum DC output at the particular frequency is necessary for better sensitivity (because phase detector sensitivity varies linearly with maximum output voltage.)

From the criteria above and upon extensive research and testing, the mini circuits SRA-1 mixer with bandwidth of 0.5-500 Mhz was selected.

B. *Mathematical Description*

Assuming two sinusoidal signals the mixer equation is:

$$I_{Fout} = A_1\cos[(\omega_{LO}-\omega_{RF})t-(\Phi_{LO}-\Phi_{RF})]+A_2 Cos[(\omega_{LO}+\omega_{RF})t-(\Phi_{LO}-\Phi_{RF})]$$

But

$$\omega_{LO}=\omega_{RF}=\omega$$

Therefore:

$$I_{Fout}= A_1\cos(\Phi_{RF}-\Phi_{LO})+A_2\cos(2\omega t)$$

Where:

ω_{LO} = Frequency of local oscillator port signal

ω_{RF} = Frequency of RF port signal

Φ_{RF} = Phase of RF port signal

Φ_{LO} = Phase of local oscillator port signal

I_{Fout} = Output of the mixer

A_1 and A_2 = Amplitude of output signals

$A_1\cos(\Phi_{RF}-\Phi_{LO})$ Is seen as a DC level, which determines the phase difference.

$A_2 \cos(2\omega t)$ Contains higher frequencies as a result of the multiplying nature of the mixer and thus must be removed from the output through filtering. Fig 5 shows a diagram of the output of the mixer prior to filtering.

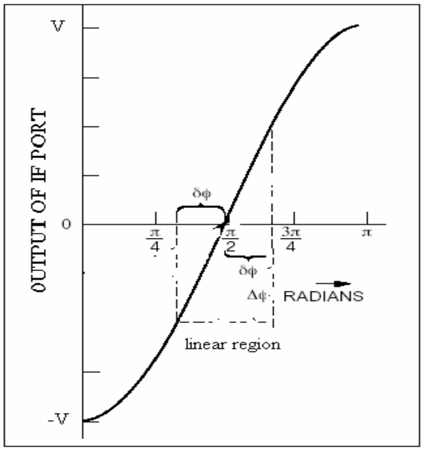

Fig 5: Graph of output signal of Mixer

The above implies that for a given system,
$VI_{Fout} = 0$ when there is a 90° phase difference ($\Delta\phi = \pi/2$)
$VI_{Fout} = V$ when the phase difference is Zero
$VI_{Fout} = -V$ when the phase difference is 180° ($\Delta\phi = \pi$).
At the VI_{Fout} port, the response to changes in $\Delta\phi$ is fairly linear over the region corresponding to $\Delta\phi = \pi/2 + \delta\phi$. It is in this linear region that the sensitivity of the phase detector to changes is maximized. However, the maximum sensitivity depends of the maximum voltages seen when $\Delta\phi = 0$ or π. Thus phase detector sensitivity varies linearly with maximum output voltage [5].

IV. DESIGN AND TESTING OF PHASE DETECTOR

A. *Preliminary Design*

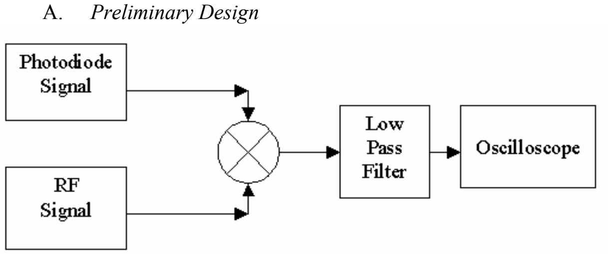

Fig 6: Block Diagram of Initial Phase Detector System

The above block diagram shows the initial design for the phase detector. In this design, the two signals (Sinusoidal RF signal and Photodiode pulse signal) were fed into the SRA-1 mixer. The output of the mixer was seen to be only the RF signal. This occurs because the photodiode signal power was below the minimum required by the mixer specifications. Therefore the design was modified to include an amplification stage of the photodiode signal.

B. *Intermediate Design*

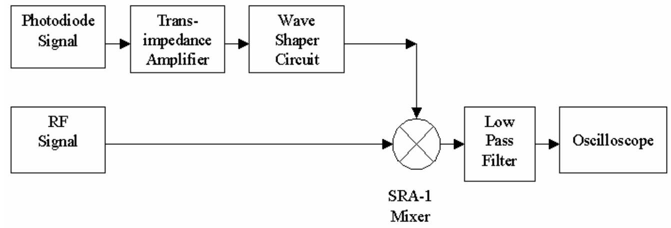

Fig 7: Block Diagram of Intermediate Phase Detector System

The signal from the photodiode is a current signal that needs to be converted to a voltage signal and amplified to a voltage that is high enough to be utilized by the mixer. A trans-impedance amplifier is used to achieve this. Also known as a current to voltage converter, the trans-impedance amplifier converts a current signal into a voltage signal whilst amplifying the signal. Because of the high frequency of the signal, an operational amplifier with a high gain bandwidth product (GBP) is needed for amplification purposes. The OPA 657 from Burr Brown with a GPB of 1.6 GHz was the best amplifier for this design in that it meets all the specifications and more [6]. A 1K-ohm feedback resistor was used producing a gain of 4. Fig 8 shows the circuit diagram for the amplifier design. Calculations for the circuit elements were made as per data sheet of the OPA 657 amplifier. A 0.01-microfarad capacitor was placed at the output of the amplifier in order to remove any DC component from the amplified signal.

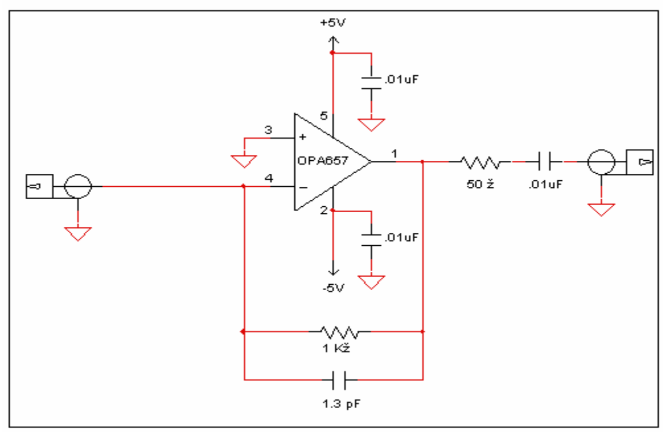

Fig 8: Trans-impedance Amplifier

The signal from the PD is a pulse with a frequency of 81.25 MHz. In order use the frequency mixer, the amplified photodiode signal must be converted to a sinusoid so as to be able to utilize the mathematical relationship that occurs as a result of the mixing action. A Low Pass Filter (LPF) is used to reshape the signal by eliminating higher order modes. A low pass filter is a circuit that discriminates between high and low frequencies and allows only the low frequencies to pass.

The cut-off frequency of the LPF must be slightly greater than 81.25 MHz. A 90 MHz Low Pass Filter from mini-circuits (PLP-90) was used to produce the desired 81.25 MHz sinusoidal signal [7]. The reference 81.25 MHz RF signal and the modified 81.25 MHz photodiode signal are input to the LO and RF ports of the mixer, respectively. The output of the mixer is sent through a Low Pass Filter (20 MHz) to remove the higher harmonics leaving only the DC component, which is used to tell the phase difference between the two signals after calibration.

To calibrate the phase detector (mixer), an RF signal of approximately 81.25 MHz from a function generator and the reference signal are fed into both inputs (LO and RF) of the mixer. The amplitude of the resulting sine wave at the output of the mixer varies with increasing input power levels. For this reason, the calibration was repeated for different input power levels. For the optimum detector level (the power level equivalent to that of the reference RF signal and the modified PD signal), the calibration was found to be 3-millivolt of phase-detector output per degree. The DC level ranged from negative 100 mV to 100 mV corresponding to 180-degrees and Ø-degrees phase difference, respectively. Ø mV corresponds to 90-degrees phase difference.

1. Measurement of phase difference over time

The main purpose of the phase detector is to measure the relative phase difference between the two signals. As such, a delay cable can be utilized to set the relative phase to a constant so as to be able to measure it over time. In this experiment, the relative phase difference was set to 0-degrees (near maximum amplitude) and measured over time to determine whether the slope of the signal varied with changing amplitude and phase. The measurements were taken using an oscilloscope because more stable readings were obtained than with a multi-meter. Table 2 below illustrates the data taken over time on two different days and Fig 9 shows the resulting graph.

Time	Phase Difference (mV) [Day1]	Phase Difference (mV)[Day 2]
2:00 PM	100	88
2:15 PM	96	80
2:30 PM	96	218
2:45 PM	94	220
3:00 PM	94	218
3:15 PM		218
3:30 PM		214

Table 2: Phase Difference recorded over time

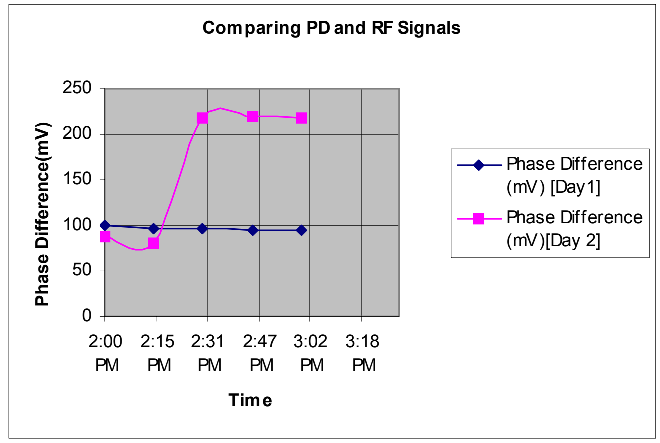

Fig 10: Graph of Relative Phase Difference

2. Discussion

From the graph of Fig 10, one can observe that the relative phase difference recorded on day one was almost constant, varying by a maximum of 6 mV (2-degrees) from the start of the experiment to the end. However, the phase difference recorded for day two saw a large jump between 2:15 pm and 2:30 pm after which it remained almost constant. Because the change in DC level exceeded 100 mV (maximum DC level calibrated), the change was associated with an increase in the input signal level rather than a phase change.

The uncertainty introduced in the data as a result of this observation necessitated the redesigning of the system such that increases in input amplitude did not affect the phase difference. Also, because the linear range of the mixer was so minuscule (3 mV per degree), its sensitivity is low. The final prototype of the design was modified to include an amplitude limiter at the input and an amplifier at the output.

C. Final Design

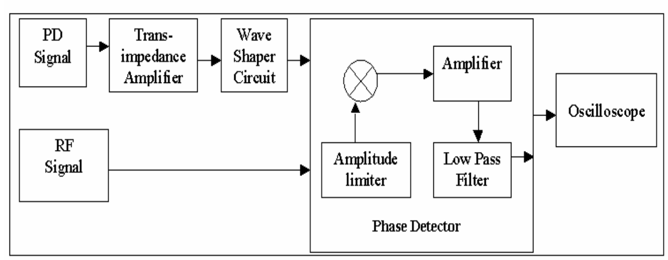

Fig 11: Block Diagram of Final Phase Detector System

The AD8302 RF/IF Gain and Phase Detector from analog devices [8] has an input frequency range of greater than zero MHz to 2.7 GHz. It consists of a limiter at its inputs, an amplifier, and a LPF at the output as shown in Fig 11.

The limiter keeps the amplitude of the input signals constant and eliminates the dependence of the phase error signal (phase difference) on amplitude fluctuations. The amplifier magnifies the output signal and thus increases the linear range and sensitivity of the detector. The LPF eliminates higher harmonics from the output signal leaving only the DC component. The dynamic range and bandwidth of the AD8302 was measured to be from -47 dBm to 3 dBm and 1.3 MHz, respectively. The phase detector was calibrated as described in section B1 and the calibration was found to be 9.7-millivolt of phase-detector output per degree. The DC level ranges from 30 mV to 1.77 V, which corresponds to 180-degrees to Ø-degrees phase difference, respectively; 930 mV corresponds to 90-degrees phase difference. This is illustrated in Fig 12 below.

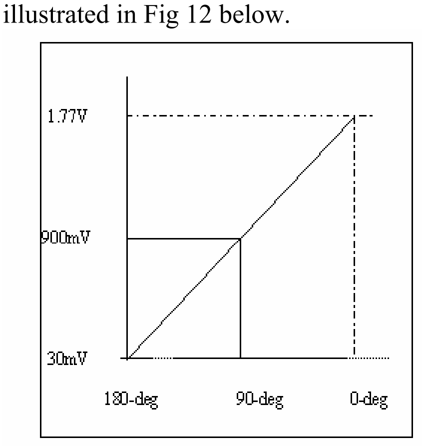

Fig 12: Transfer Function of Phase Detector.

1. *Measurement of phase difference over time*

In this experiment, the relative phase difference was set to 0-degrees and measured over time to observe if it varied. The measurements were taken using a digital multi-meter. Table 3 below illustrates the data taken over time and Fig 13 depicts the resulting graph.

Time	Phase Difference (V)	Phase Difference (Degrees)
2:00 PM	1.770	0
2:15 PM	1.770	0
2:30 PM	1.769	0.1
2:45 PM	1.770	0
3:00 PM	1.770	0
3:15 PM	1.770	0
3:30 PM	1.769	0.1

Table 3: Phase Difference recorded over time

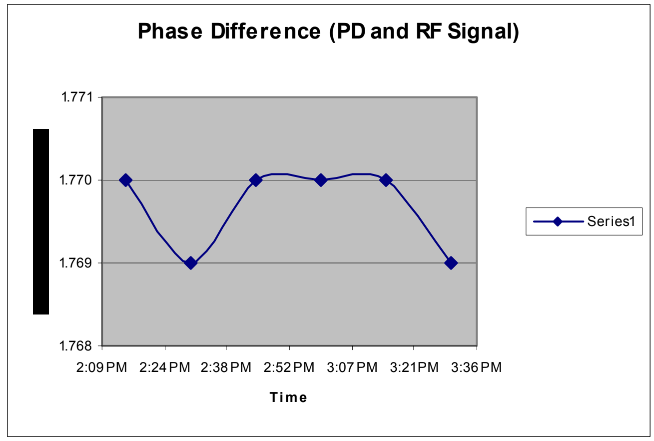

Fig 13: Graph of Relative Phase Difference

2. *Discussion*

From the graph of Fig 13, it can be seen that the relative phase difference remained almost constant varying only by a tenth of a degree. This results reveals that the laser is phase locked to the RF with a phase jitter of less than 2.1 ps (0.3 ps), meeting the requirement of TESLA.

3. Comparing Error Signal of External Phase Detector to Laser Room Phase Detector (Internal PD)

In this experiment, the relative phase difference of the external phase detector and the internal phase detector were recorded over time. The phase difference of the external phase detector was set to 0-degrees and compared to that of the internal phase detector, which was also at 0-degrees. The data is shown in Table 4 and the resulting graph is depicted in Fig 14.

Time	External PD Phase Difference 1 (V	External PD Phase Difference 1 (Degrees)	Internal PD Phase Difference 2 (V)	Internal PD Phase Difference 2 (Degrees)
3:00 PM	1.770	0	0	0
3:15 PM	1.770	0	0	0
3:30 PM	1.769	0.1	0	0
3:45 PM	1.770	0	0	0
4:00 PM	1.770	0	0	0
4:15 PM	1.770	0	0	0
4:30 PM	1.769	0.1	0	0

Table 4: Comparing Error Signal of External PD and Internal PD

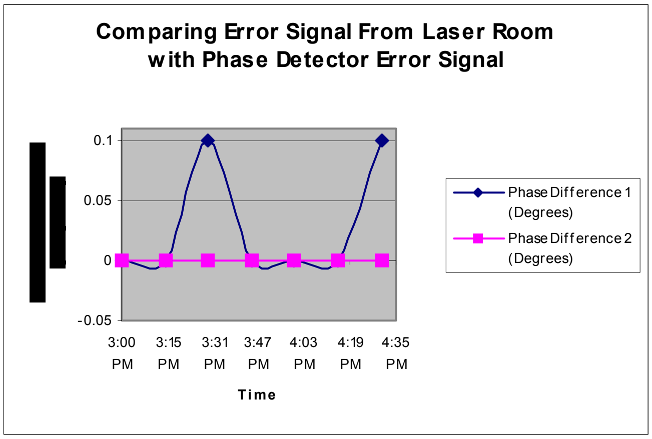

Fig 14: Graph of Error Signal of External PD and Internal PD

4. Discussion

The above results show the phase detector in the laser room (internal phase detector) with a constant phase error signal of 0-degrees, implying the stability of the phase relationship among all modes. The external phase detector, however, illustrates a deviation of 0.1 degrees of the laser phase from the RF phase.

V. CONCLUSION

Using the results obtained from the above experiments, it can be concluded that the "phase error signal" of the two systems agree within 0.1-degrees. Although more investigation needs to be made, it would be desirable to replace the phase detection circuit of the commercial phase locked box with a more accurate circuit such as the external phase detector described in this paper to assure the stability of the laser output.

VI. ACKNOWLEDGEMENT

I would like to thank my supervisor, James Santucci for his leadership and guidance. I also want to express my sincere gratitude to Rene Padilla and Nikolai Barov for their invaluable assistance and practical advices on this project. I would like to extend my appreciation to Dianne Engram, Elliott McCrory, David Peterson, James Davenport and the entire SIST committee for giving me this great opportunity.

VII. REFERENCES

[1] M.J Fitch, Electro-Optic Sampling of Transient Electric Fields from Charged Particle Beams.
[2] A. R. Fry, Novel Pulse Train Glass Laser for RF Photo-injectors.
[3] P. Horowitz and W. Hill, The Art of Electronics, Cambridge University Press 1989
[4] S. Kratzet, "PLL Hardware Design and Software Simulation using the 32-bit version of SystemView", Elanix Inc.
[5] www.wj.com/pdf/technotes/Mixers_phase_detectors.pdf
[6] http://focus.ti.com/lit/ds/symlink/opa657.pdf
[7] http://www.minicircuits.com/dg03-194.pdf
[8]http://www.analog.com/UploadedFiles/Data_Sheets/797075782AD8302_a.pdf